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Universal Interconnect Needs and Trends

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Executive Summary

In the future, power distribution systems now controlled by large providers of power generation will be replaced by more distributed power generation architectures where the lines of demarcation between providers and users of power are less restrictive. The industry is concerned about how existing power distribution systems can accommodate such a changeover within the next 5-10 years and also about how this changeover will affect the economics of power delivery and even the implementation of new power distribution architectures and controls. One of the key issues is distributed generation – electric power system (DG-EPS) interconnection, which has fundamental impacts on current EPS operation and future DG penetration.

The interconnection issue is currently being actively addressed, led by US Department of Energy, among different communities, including regulatory, research institutes, standard organizations, utilities, and DG vendors.

This white paper will address DG/EPS interconnection needs and trends from an industry perspective. A conceptual interconnect design will also be presented.

1. Universal Interconnect Needs and Trends

1.1 Interconnection Issues

Traditional non-utility generated power sources, such as emergency and standby power systems, have minimal interaction with the electric power system. As Distributed Generation (DG) hardware becomes more reliable and economically feasible, there is an increasing trend to interconnect those DG units with the existing utilities to meet various energy needs, as well as to offer more service possibilities to customers and the host EPS.

However, a wide range of system issues arise when the DG units attempt to connect to the Electric Power Systems (EPS). Major issues regarding the interconnection of DG include protection, power quality, system reliability and system operation. Another complex issue is interconnection cost, which involves equipment design, industry standards, and the local utility's approval process. These are some of the issues that have been identified as barriers to the application of DG in the EPS[1]. The solutions to these technical challenges will help not only shape the future of electric power generation, transmission, and distribution systems, but will also have a profound impact on the economics.

To promote the application of distributed generation, the following steps need to be taken. First, a widely accepted interconnection standard is needed that will allow for a standardized, cost effective interconnection solution. The IEEE SCC21 P1547 standard working group is currently working towards this goal. Second, new technical requirements that address the emerging needs of DG for dispatch, metering, communication and control should be fully explored. These additional features will improve the value of DG and the performance of the system.

1.2 Current Interconnect Status

The complexity of the DG/EPS interconnect interface increases with the level of interaction required between the DG units and the grid.

- Standalone only - There is no interaction with grid. No interconnect is required.
- Standby – DGs do not directly interface with the utility grid, but are connected to the local system when the utility grid is not available. Therefore, the DG has minimal interaction with grid. In this case, a transfer switch can be used as the interconnect.
- Generation of power for consumption solely for the local load: this type of DG is fully interconnected to the grid. It normally does not export power to the grid.
- DG with import/export power – this type of DGs has complex interconnect requirements. These DGs are normally integrated in the EPS control/monitoring.

To meet the above application needs, a variety of interconnect products are available in the market. They can be categorized as: power-carrying devices (PCD), protection and control devices, and inverters.

[1] National Renewable Energy Laboratory, "Making Connections: Case Studies of Interconnection Barriers and Their Impact on Distributed Power Projects," US Department of Energy, May 2000.

1.2.1 Power-Carrying Devices

The power-carrying devices include switchgears such as, circuit breakers, automatic paralleling/transfer switches, etc., as well as transformers for the purpose of isolation or grounding. While the major purpose of the power-carrying devices is to conduct and break current, some of the devices have incorporated some protective functions as well. The power rating of these devices can range from several kVA to a few MVA.

1.2.2 Protection and Control Devices

The protection and control devices include generator controllers, protective relays, etc. Increasingly, these functions are implemented by a class of device known as an intelligent electronic device (IED). These devices are microprocessor-based for programmable control and protection, such as synchronous checking, over/under voltage, over/under frequency, directional power, directional reactive power, reverse phase/phase-balance current, phase sequence voltage, voltage-restrained over-current protections, etc. Some of them have communication capabilities. Most of them, however, do not have dedicated anti-islanding control. These devices do not directly switch or otherwise directly handle the power. They are used together with power carrying devices to execute their protective and control functions.

1.2.3 Inverters

Another DG component important to the interconnection is power electronics inverters. The inverter is used as power-carrying devices to interconnect DG energy sources, which produce DC, or produce AC at other than 60 Hz, with the grid. It is possible to implement most protective and control functions required for interconnection onto a single board that also controls inverter operation.

Generally, utilities have less confidence in the protective functions integrated into the inverters because these devices are not utility-grade protection hardware, and because the protective functions are not independent from the power components that could possibly fail in a way that adversely affects the grid system.

Currently, there are different standards and requirements in different states for DG interconnection. It is essential from the points of view of universality, modularity, and scalability to have a solution that addresses those requirements as shown in a multi-dimensional space in Figure 1. The DG technology can range from small photovoltaic units to large cogeneration plants. The power interface between the DG prime mover and the grid can be single-phase or three-phase power electronic converters, or rotating machines. The power range can be from under 5kW to greater than 500kW for larger systems.

There are multiple technology dimensions in DG applications. Regulatory and market forces will drive different aspects of the technologies selected. Each stakeholder will try to minimize the interconnect cost and maximize the benefits from its own perspective. This situation could result in one or two parties incurring minimal costs, while the cost is not acceptable for other parties. Eventually, it will prohibit DG achieving widespread acceptance in practical applications.

In order to achieve the broadest benefits from DG, regulators and markets, including those who set the interconnect standards, have to provide the correct price signal. Those laying out capital for an interconnection will seek to incur the least cost possible by providing the bare minimum functionality required to allow their DGs to meet safety and reliability requirements. This minimum functionality may not adequately serve the broader needs of the power system, and so, economic rewards need to be provided to those bearing the cost in order to assure that the additional functionalities beneficial to all are implemented.

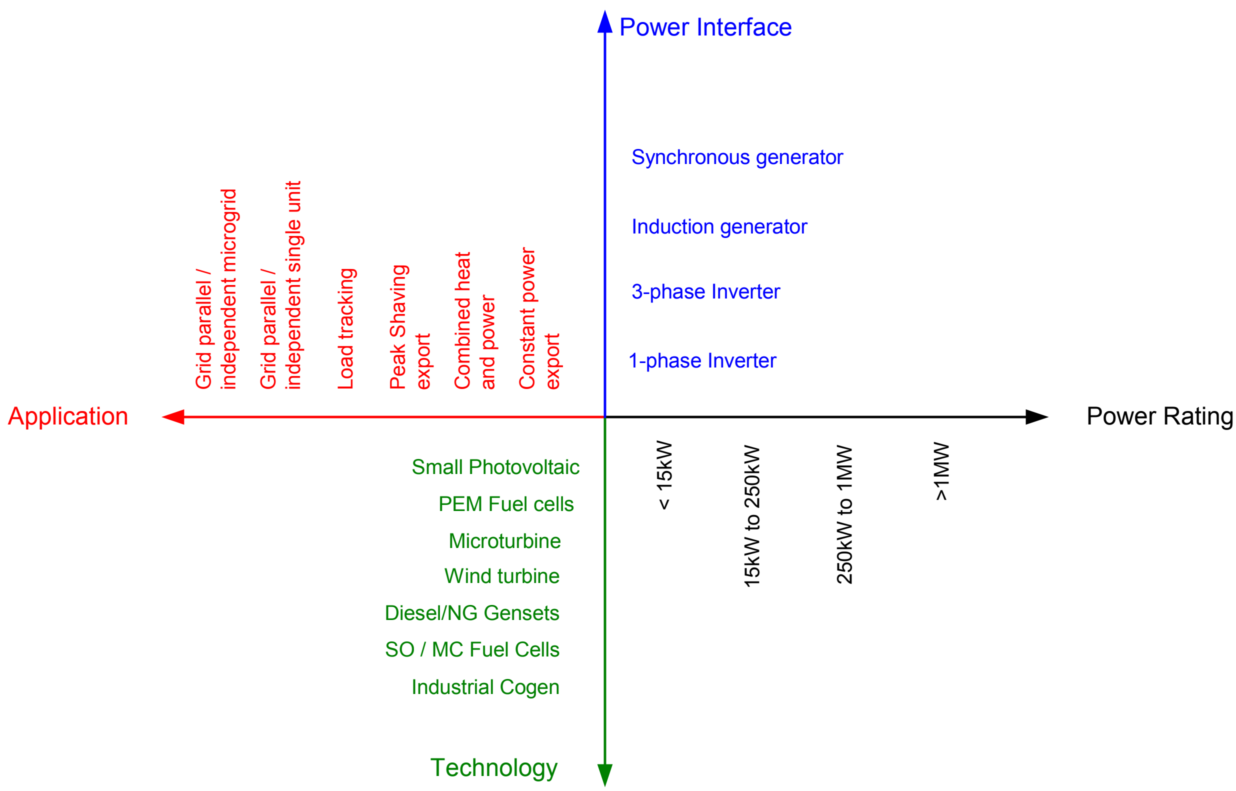

Figure 1 DG in a multi-dimensional space.

It is observed that many solutions are targeted for specific applications. For example, some solutions are targeted for photovoltaics, while some solutions are especially suitable for rotary DG. Furthermore, it is observed that few solutions are designed such that they can be used as building blocks for providing solutions for future requirements. The goal of a new interconnect solution is to minimize overall system cost and to maximize value to the individual DG owner and the grid users in general.

1.3 Future Interconnect Needs and Trends

A conceptual design that addresses a technology neutral, modular, scaleable solution is desirable for the future interconnect solution. For widespread acceptance in the market, the solution has to involve a low cost approach. Existing solutions are so far not able to satisfy all requirements addressed in the multi-dimensional space shown in Figure 1. However, it should be noted that not all features would be required for all applications. Hence, a universal solution should be designed modularly, such that it can be a building block for future solutions. This would allow it to meet the need for universality, modularity, and scalability; at the same time covering all requirements addressed in the multi-dimensional space.

As noted above, a minimum of functionality may not well serve the broader needs of the power system, and yet this minimum functionality provides a basis on which to build broader, and more widely beneficial functionality. A closer examination of the requirements and benefits shows that there is a natural progression of functionality of the universal interconnect. Figure 2 shows a diagram representing the increasing levels of functionality that are required for interconnection.

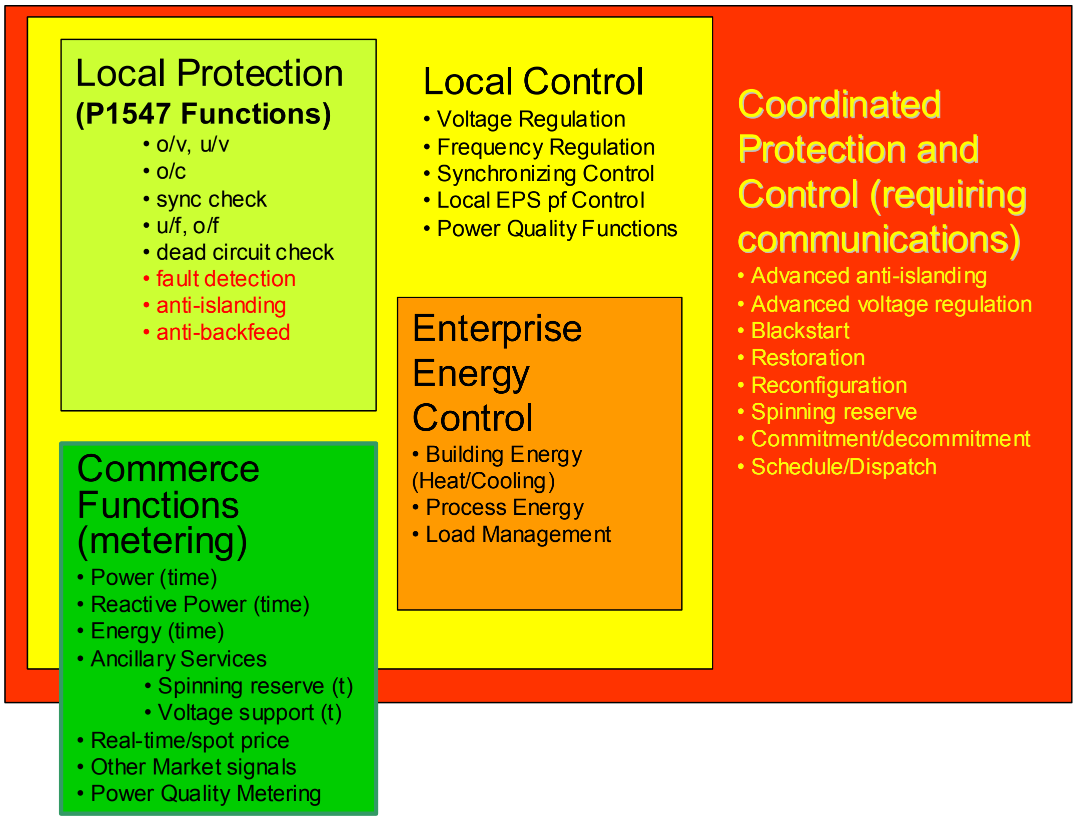

Figure 2 Global functionality of universal interconnection.

In general, each subsequent stage of complexity wholly incorporates the functionality of the previous level. This overall, long-term concept consists of following levels:

- Local Protection
- Local Control
- Coordinated Protection and Control
- Enterprise Energy Control
- Commerce

Each of these levels imposes functional requirements, which are examined in some detail in the following subsections.

1.3.1 Local Protection

The most basic set of protective functions that are required for interconnection are shown in Figure 3. These functions roughly correspond to P1547 requirements. These functions can be accomplished with local measurements. Most of the functions are simple, can be accomplished with existing relay functions, and are largely met by commercially available devices. The most notable exception is that the anti-islanding and fault detection functions required by P1547 are relatively complex, and not readily available. There is no method that is effective for all circumstances. From a power system reliability perspective, these local protective functions are basically aimed at limiting potential adverse impacts of DG on the host EPS.

Three functions, fault detection, anti-islanding and anti-backfeed impose restrictions on the DG performance which are generally incompatible with the requirements of some of the higher level functions discussed in the next section. They are highlighted in red, to emphasize this incompatibility.

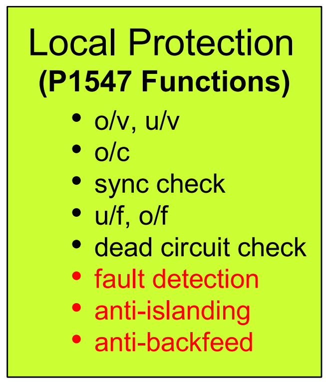

Figure 3 Local protection functions.

1.3.2 Local Control

These are local functions, but include a range of controls that increase the value of the DG asset. The functions, shown in Figure 4, push the DG performance in the EPS further.

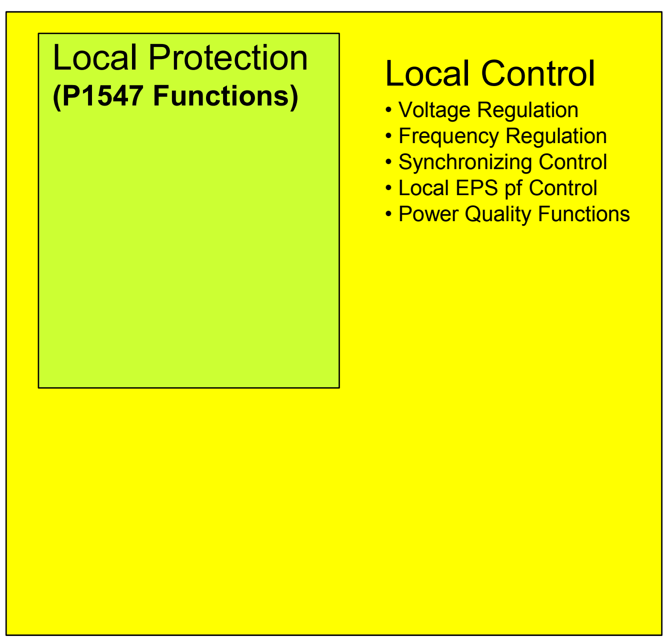

Figure 4 Local control functions.

They represent requirements that may be incompatible with P1547, though most of them could be incorporated in the DG. Further study would be required to determine exactly which control functions need to reside in the interconnect. From a reliability perspective, these functions provide the potential for improvements for the local EPS. These functions are basic to the operation of a local EPS when separated from the area EPS. For grid parallel operation, these capabilities have the potential to be either beneficial or disruptive to the reliability and operation of the area EPS. Regulation functions, both voltage and frequency, are largely incompatible with the anti-islanding and anti-backfeed provisions of P1547. To fully realize system benefits, this level of the interconnect may require relatively sophisticated means of selecting or even determining the most appropriate control mode. Other value adding functions, most notably controls aimed at improving local EPS power quality, can be included at this level.

1.3.3 Coordinated Protection and Control

The ability of DG to be incorporated into a distribution system using only local measurements is very limited. Many protection and control concerns cannot be addressed without communication. The distinction between protection and control becomes unclear in a networked system, and so there is little value in making the distinction.

This level of functionality, as shown in Figure 5, represents the range of functions that would be needed to make a system with significant DG penetration function properly and reliably.

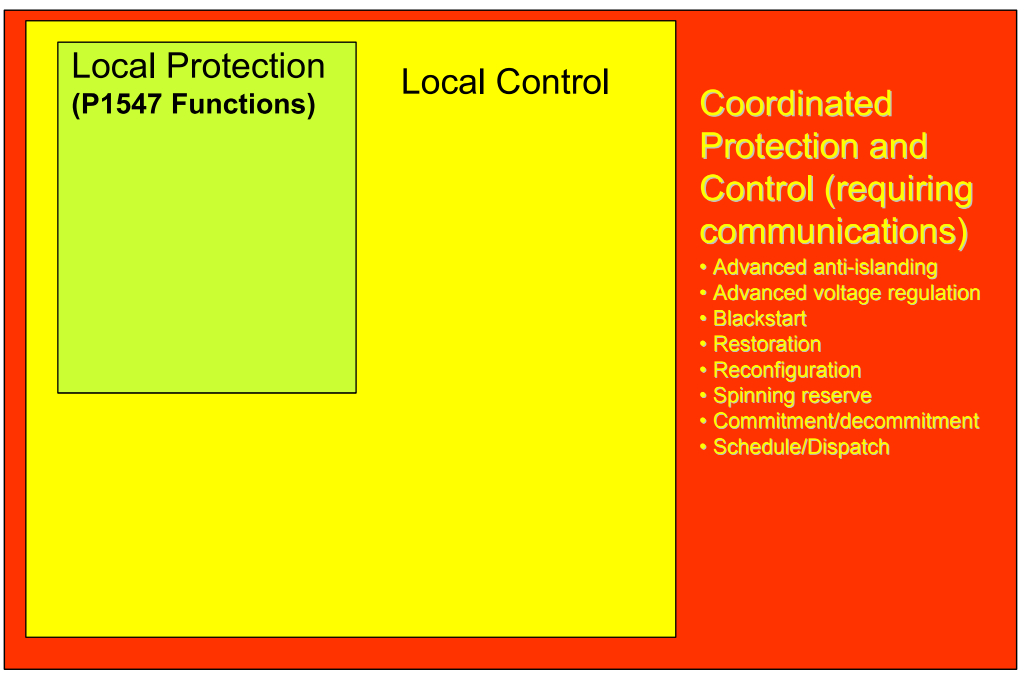

Figure 5 Coordinated control and protection functions.

This level of functionality could include microgrids. All the functionality included in the level is aimed at improving performance and reliability of the electrical system (area EPS). The need for coordinated protection and control is especially acute from the perspective of system reliability. Networked communications are essential to the successful integration of a significant DG capacity. Regulation and restoration of systems cannot be made solely based on local signals.

Economic operation of the systems, including peak shaving and more sophisticated functions such as commitment and dispatch, will require system level communication.

1.3.4 Enterprise Energy Control

In order to achieve the full benefit of DG, integration with other energy functions is desirable. The functions listed in this level, as shown in Figure 6, are complementary to the electrical protection and control requirements. Much of the economic analysis of DG shows that the most cost-effective system includes other aspects of energy management. Of particular interest is space heating and cooling, but other energy aspects may be important as well (e.g. gas and water management). This level is shown as a local function, e.g. for a building or a facility, but could conceptually be extended to multiple, physically separate facilities.

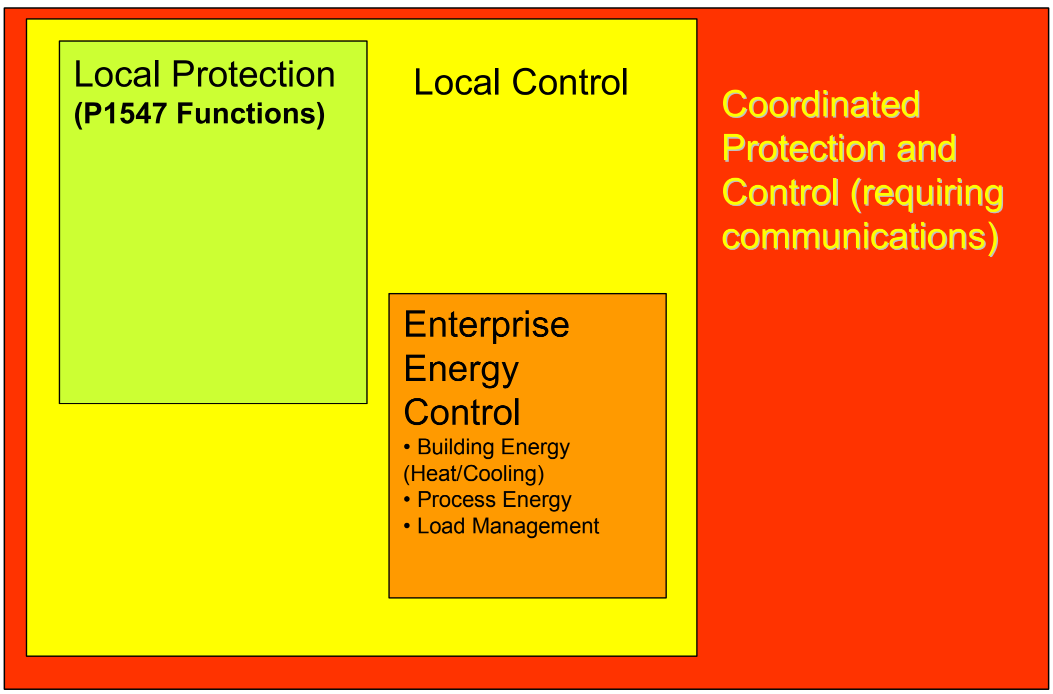

Figure 6 Enterprise energy control functions.

1.3.5 Commerce

There is an entire additional layer of monitoring, metering and control that relates to the business of owning and running DG. These functions may be localized or with significant communication and central processing (e.g. a DG aggregator or marketer). The functions listed in Figure 7 may be either completely localized or incorporate a broader communication system, as suggested by the placement in the figure. Market signals may be passed to various commercial stakeholders, most notably the DG aggregator selling and buying services from system operator.

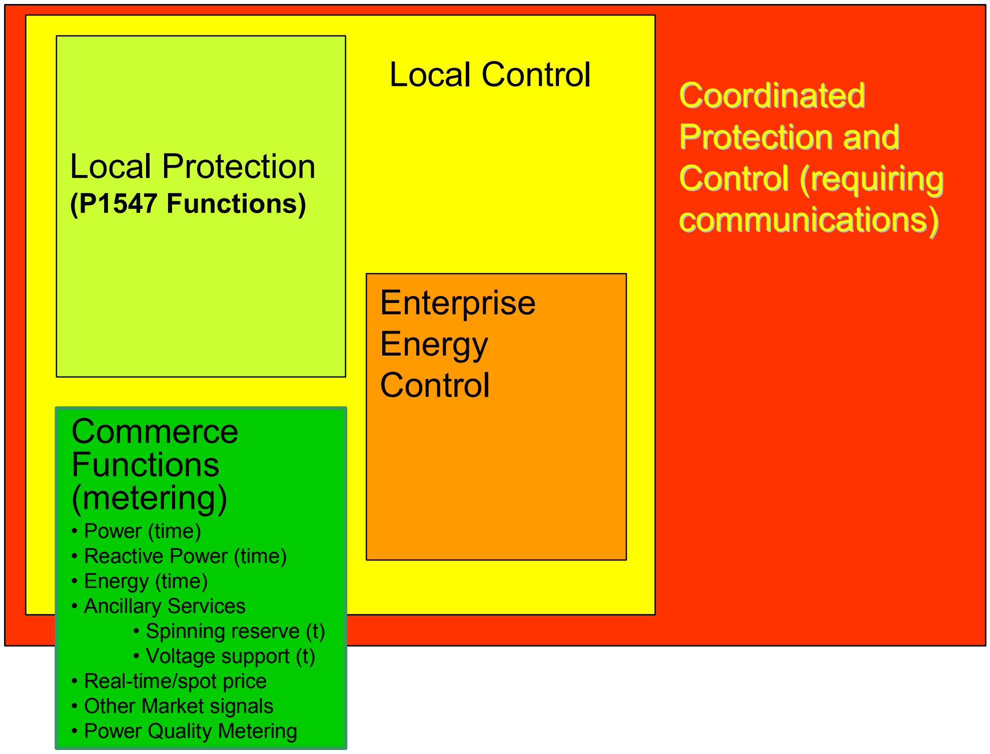

Figure 7 Commerce functions.

2. Conceptual Universal Interconnect Design

2.1 Interconnect Technology Roadmap

Having addressed the requirements for the universal interconnect design, the next questions that need to be addressed are:

- How can these different functionalities be implemented for a variety of solutions?
- What are the specific applications considerations that need to be addressed?
- What is the implementation of one particular instance of the universal interconnect?

Given that the functionality illustrated in Figure 2 has to be implemented in the DG space shown in Figure 1, it is necessary to identify various embodiments of the universal interconnect. It is envisaged that this can be realized with a modular core architecture that can be adapted to different configurations depending on the nature of the DG system. Figure 8 illustrates a possible method through which one can arrive at the required interconnect configuration with a minimal number of decision points. The final leaves in the tree shown in the figure will provide all the modules required to obtain all the functionality in Figure 2 for a given DG.

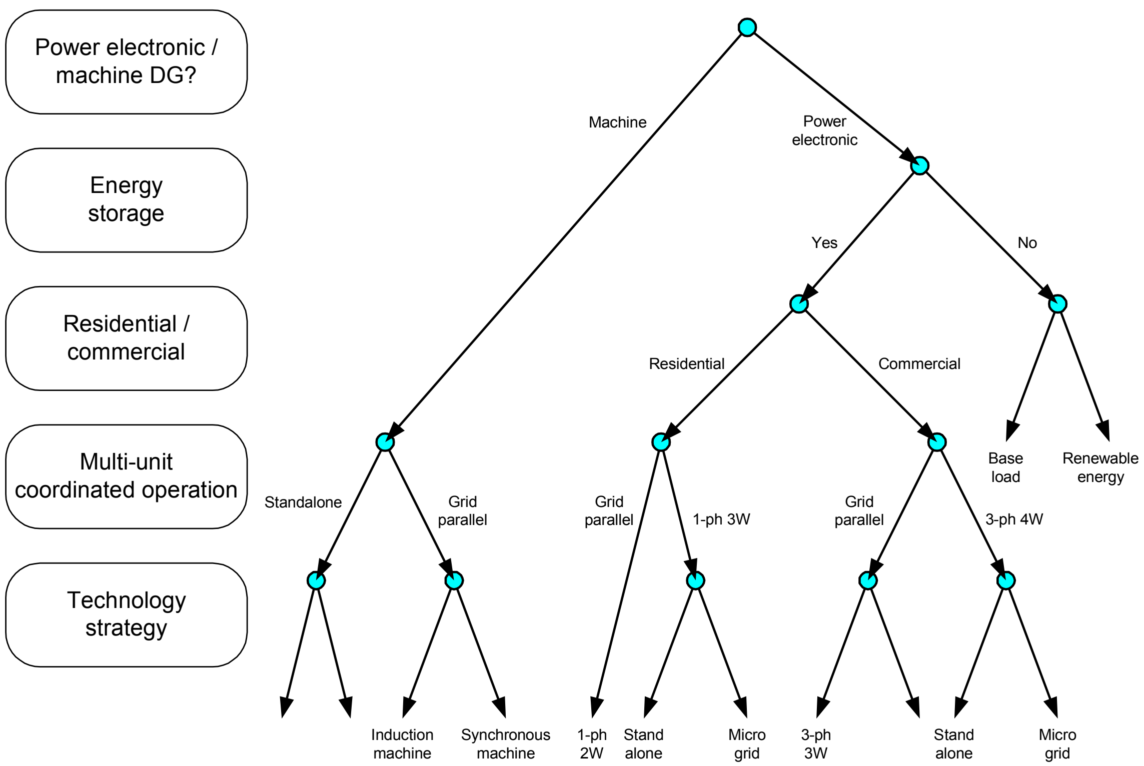

Figure 8 Interconnect function decision tree.

As distributed generation hardware becomes more reliable and economically feasible, there will be a trend towards exploiting more of the features outlined in the preceding discussion. The interconnected DG units and therefore the interconnection must evolve to reflect these progressively higher levels of functionality. This increase in functional requirement provides a logical roadmap for the development of a universal interconnect. Figure 9 shows this evolution in three generations. The development of a universal interconnect utilizes a virtual test bed and a beta test site to validate each higher level of functionality.

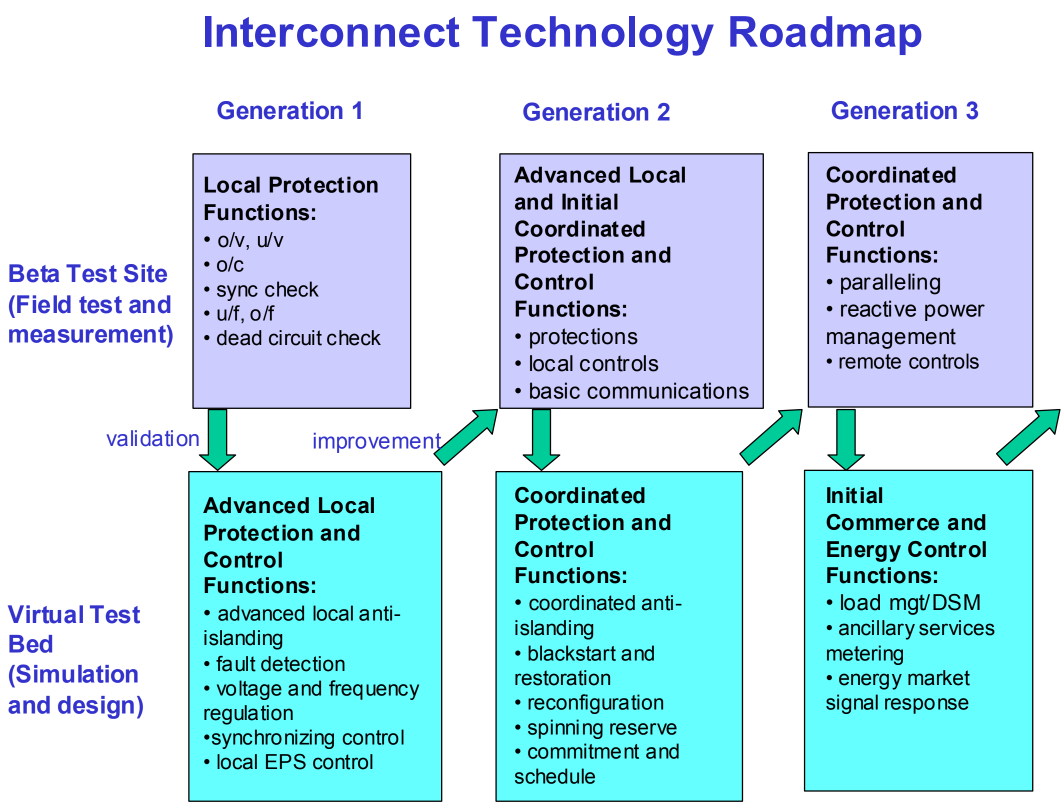

Figure 9 Interconnect technology roadmap.

2.2 Universal Interconnect Conceptual Design

Basic Features

This section presents a conceptual interconnect design example. As discussed above, because there are various product packages existing already for Generation 1 interconnect, the example presented here is targeting at generation 2 interconnect.

The key features are outlined below, referring to Figure 10.

- The interconnect is a standalone box to interfacing DG and grid. It is technology neutral and can be used for different DGs.
- There are two major modules in the interconnect box. One is Power Carrying Devices (PCD), and the other is Intelligent Electronic Devices (IED). The interfaces between these two modules should be normalized to allow for plug-n-play.
- There are four types of interfaces, as marked in Figure 10: I1) power interface to link DG and grid; I2) measurement interface to obtain voltage, current and others status; I3) control signal

interface to send/receive I/O status and controls; and I4) communication interface for the interconnect to communicate with DG and the grid.

- PCD components are chosen and placed based on application needs, such as single- or three-phase, peak shaving, critical load, etc. Figure 10 shows three circuit breakers that represent only one particular case. Besides, the ratings of these devices are determined by grid voltage and DG current ratings.
- IED is the brain of the interconnect box. All protection, control, and communication software/firmware are designed in the device.
- The functions in the IED are modular to allow for reconfiguration and upgrade.

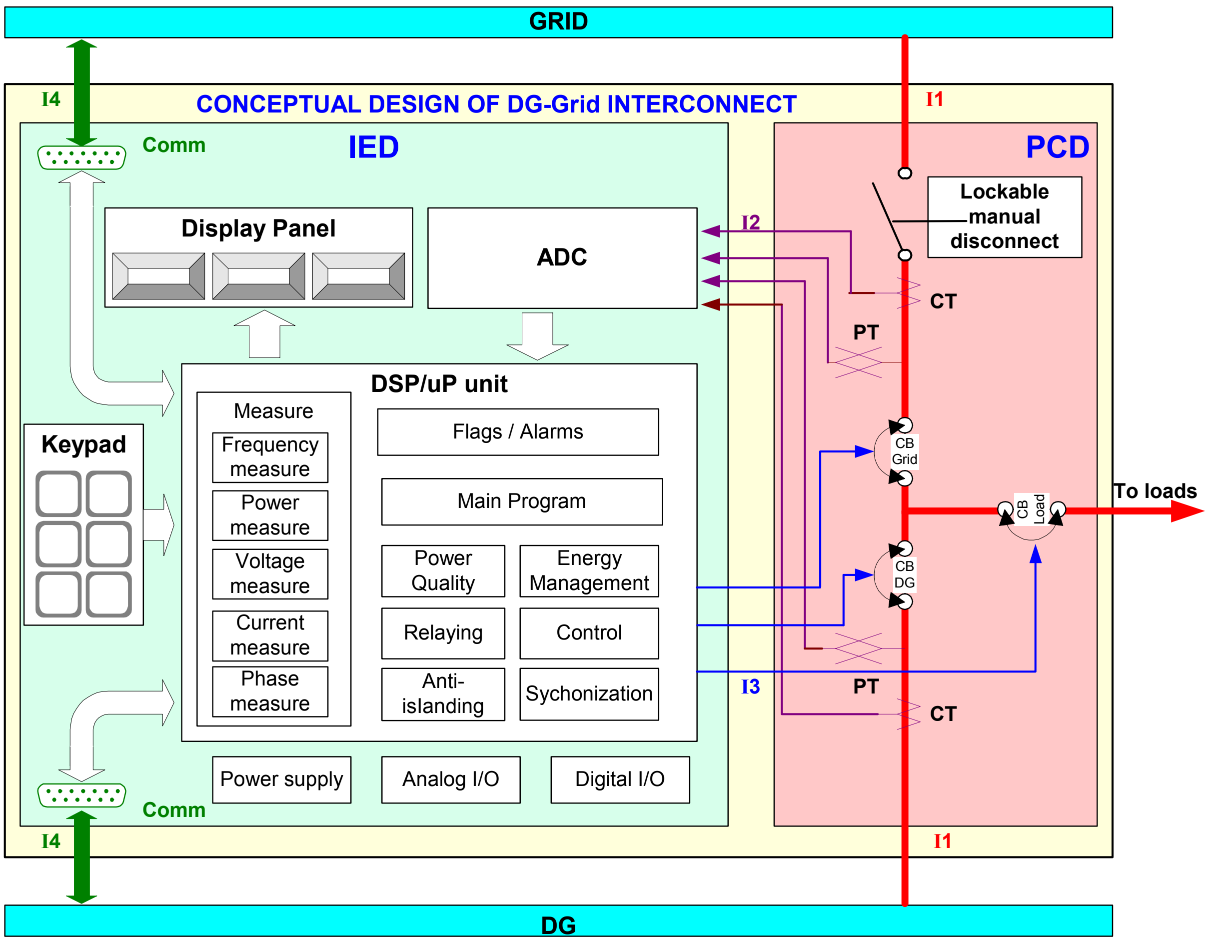

Figure 10 Conceptual interconnect design.

Interconnection Interfaces

Physically, the interconnect box is a standalone box with two types of interfaces to the DG and the grid. One is power interface, which connects the grid on one side and the DG on the other. The other one is communication interface, which links the DG locally or remotely and the grid remotely.

- Power Interface: The power interface could be single-phase two or three wires, or three-phase three or four wires. This will determine the number of cable/wire connections as well as sensors. Besides, the interface will determine the ratings of power-carrying devices (PCD), such as circuit breakers, and determine the ratings of sensors, such as CT and PT.

- Communication Interface: The communication interface is more complex than power interface. Depending on the communication needs, different communication protocols can be used. Physically, it could be wireless or wired. In order to be integrated with the grid and DG, it should have an open architecture and, at least at physical layer, be fully compatible with grid and DG communication protocols, such as RS series or Ethernet. The communication speed is dependent on the control needs. It is also desirable that the interconnect's communication capability is upgradeable and scalable.

Functional Modules

To make the interconnect technology neutral, it is important to partition the interconnect into two major parts.

1) Power-Carrying Devices (PCD): This part includes sensors and connect/disconnect devices, such as circuit breakers, switchgear, etc. The selection of these devices depends on DG-grid point of common coupling (PCC). The grid voltage and DG power ratings must be known to select these devices. In this part, besides the power path, there are two other types of signals. One kind is sensor signals going to the IED, and the other are control signals coming out of the IED. In order to have plug-and-play and user-reconfigurable feature, the interface of these two signals must be normalized. For example, the secondary of the sensors is normalized to 120V, regardless the rating of the primary, for example 480V or 575V. The control input for the connect/disconnect devices should also be normalized. This way, the PCD and IED can be plug-and-play regardless of the voltage and current levels at the point of interconnection.

2) Intelligent Electronic Devices (IED): this part is the brain of the interconnect.

- The input to the IED includes a) sensed signals from PCD part, b) communication signals from the local DG and others, such as EPS operator, ISO, enterprise energy management systems, or other DGs, and c) manual command from keypad.

- The output of the IED is a) control signals to open / close connect / disconnect devices in PCD and b) communication signals sending to DG and grid, if the communications are two-way. The signals sent to the DG can be on/off, power command, etc. The signals sent to the grid can be power import/export data, etc. c) monitoring signals in the display panel can be power, energy meter, harmonics, etc.

- These inputs and outputs will be processed by digital signal processors (DSP) through A/D and D/A converters. Inside the DSP, different functions needed for the interconnection are programmed. These functions include
  - Computation of frequency, power, etc. as measurement function. The measurement can be used for display, computing other data, and even accessible remotely as log data for DG and grid operators.
  - Protective relaying function, such as over/under voltage, over/under frequency, etc. These relay functions are adjustable to meet different requirements and application needs.
  - Synchronization function: Before the DG connects to the grid, the DG output voltage and frequency should be synchronized. This function will sense the grid voltage and frequency and compare them with DG output voltage and frequency. When they are matched closely enough, the function will send a command to close the power-carrying devices for interconnection with the grid. If they are not matched, instead of waiting for the DGs voltage and frequency to approach the grid voltage and frequency naturally, the interconnect may send the grid voltage and frequency signals to the DG as references for the DG to adjust its voltage and frequency.
  - Anti-islanding: this is a unique function of the interconnect box. Many schemes exist today. Most passive schemes can be done within the interconnect box, while some of them require additional hardware, for example, transmitter and receiver. Most active schemes need coordination and communication with DG controls. From modular and standardization point of view, an effective scheme built in the interconnect box would be more desirable. This function will be a key effort for the generation 2 interconnect development.
  - Control: the interconnect may need some control functions, for example, control the power factor to improve voltage regulation. The control may need to be coordinated through the local and remote communications.
  - Energy management: this is a system level function that optimizes the DG value. For example, it dispatches DG for peak-shaving or base load based on daily energy rate, which could come from utilities or Independent Service Operator (ISO) through communications. The bandwidth of this control can be very low, for example, in minutes or even hours.
  - Power quality: most standards have power quality requirements imposed on the DG and grid point of common coupling, and do not distinguish between the requirements for the interconnect and DG. One of the key values of the standardized interconnect is that it can be pre-tested and pre-certified against the standards. This feature will facilitate DG installation process. Therefore, it may be necessary for the interconnect to measure power quality, such as harmonics, DC current injection, etc. If the power quality does not meet the standards, the interconnect box can command disconnection of the DG.
- Additionally, power supplies are needed to power the chips in the IED. Additional analog I/O and digital I/O also may be needed for upgrade and expansion.

The proposed interconnect concept is modular, scalable and technology neutral. This allows for maximum flexibility when interfacing to a variety of DGs for different applications.

3. Summary

In summary, the development of a universal interconnect can follow a natural progression of functionality. The basic requirements imposed by the various interconnection standards, most notably IEEE P1547, provide a foundation on which higher levels of functionality can be built. These higher levels of functionality benefit both system reliability and the economics of DG. Thus, the universality of the interconnection device should be viewed as a platform on which the functions required to maximize the economic and performance benefits of DG can be built, rather than a single device that will allow all possible DG to be uniformly connected to any host electric power system.